Diffused p-n Junction Silicon Rectifiers

By M. B. PRINCE

(Manuscript received December 12, 1955)

Diffused p-n junction silicon rectifiers incorporating the feature of conductivity modulation are being developed. These rectifiers are made by the diffusion of impurities into thin wafers of high-resistivity silicon. Three development models with attractive electrical characteristics are described which have current ratings from 0 to 100 amperes with inverse peak voltages greater than 200 volts. These devices are attractive from an engineering standpoint since their behavior is predictable, one process permits the fabrication of an entire class of rectifiers, and large enough elements can be processed so that power dissipation is limited only by the packaging and mounting of the unit.

1.0 INTRODUCTION

1.1 The earliest solid state power rectifier, the copper oxide rectifier, was introduced in the 1920's. It found some applications where efficiency, space, and weight requirements were not important. In 1940 the selenium rectifier was introduced commercially and overcame to a great extent the limitations of the copper oxide rectifier. As a result, the selenium rectifier has found wide usage. In early 1952 a large area germanium[1] junction diode was announced which showed further improvements in efficiency, size, and weight. In addition it shows promise of greater reliability and life as compared to the earlier devices. However, all of these devices have one drawback in that they cannot operate in ambient temperatures greater than about 100°C.

Also in 1952, the silicon alloy[2] junction diode was announced and was shown to be capable of operating at temperatures over 200°C. However it was a small area device and could not handle the large power that the other devices could rectify. During the past three years development has been carried on by several laboratories in improving the size and power capabilities of these alloy diodes. In early 1954 the gaseous diffu-

[1] Hall, R. N., Proc. I.R.E., **40**, p. 1512, 1952.
[2] Pearson, G. L., and Sawyer, B., Proc. I.R.E., **40**, p. 1348, 1952.

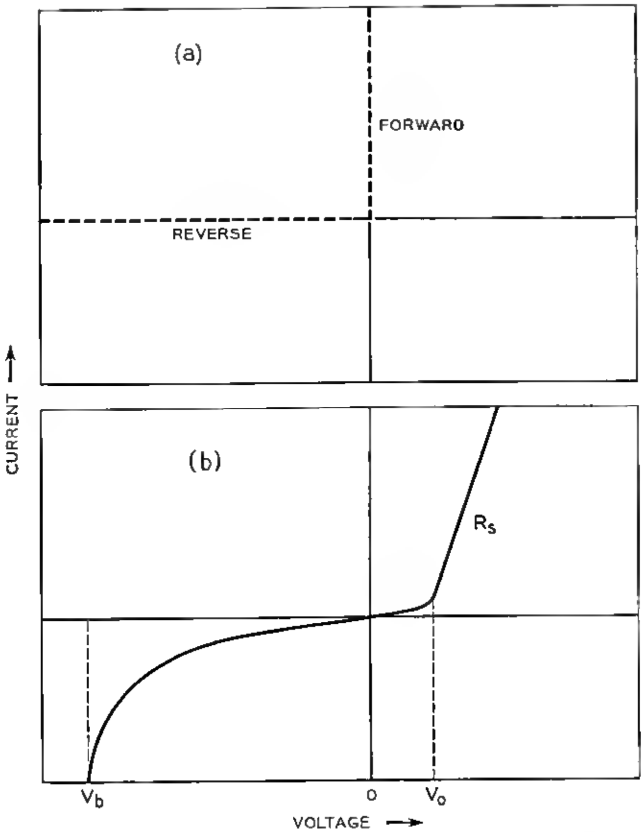

Fig. 1 — (a). Ideal rectifier. (b). Semiconductor rectifier.

sion technique[3] for producing large area junctions in silicon was announced. This technique lends itself very readily to controlling the position of junctions in silicon. An early rectifier[3] made by this technique was one half cm² in area and conducted 8 amperes at one volt in the forward direction and about 2 milliamperes at 80 volts in the reverse direction. The series resistance of this device was approximately 0.07 ohms.

1.2 In order to understand quantitatively the problems associated with power rectifier development, consider Fig. 1(a) which shows what an engineer would like in the way of an ideal rectifier. It will pass a large amount of current in the forward direction without any voltage

[3] Pearson, G. L., and Fuller, C. S., Proc. I.R.E., **42**, No. 4., 1954.

drop and will pass no current for any applied voltage in the reverse direction. At present no device with this characteristic exists. A typical semiconductor rectifier has a characteristic of the type shown in Fig. 1(b). In these devices there is a forward voltage, V_0, that must be developed before appreciable current will flow and a series resistance, R_s, thru which the current will flow. In the reverse biased direction there is a current that will flow due to body and surface leakage and that usually increases with reverse voltage. At some given reverse voltage, V_B, the device will break down and conduct appreciable currents. To have an efficient rectifier, V_0 and R_s should be as small as possible and V_B should be as large as can be made; also, the reverse leakage currents should be kept to a minimum. According to semiconductor theory, V_0 depends mainly upon the energy gap of the semiconductor, increasing with increasing energy gap. R_s consists of two parts; body resistance of the semiconductor and resistance due to the contacts to the semiconductor. The higher the resistivity of the semiconductor, the higher is the body resistance part of R_s. The leakage currents in the reverse direction depend to some extent on the energy gap of the semiconductor, being smaller with larger energy gap; and V_B depends most strongly on the resistivity of the semiconductor, being larger for higher resistivity material. Another factor that is important in the choice of the semiconductor is the ability of devices fabricated from the semiconductor to operate at high temperatures; high temperature operation of devices improves with larger energy gap semiconductors. Thus there are two compromises to be made in choosing the material (energy gap) and resistivity of the semiconductor.

1.3 This paper reports on a special class of rectifiers in which improved performance has been obtained. These devices are made by using the diffusion technique with silicon. The diffusion process permits both accurate geometric control and low resistance ohmic contacts, which in turn makes it possible to reduce R_s to very small values independent of the resistivity of the initial silicon. Therefore, high resistivity material can be used to obtain high V_B. An explanation of this result is given in Section 3. Silicon permits small reverse currents and high temperature operation. Its only drawback is that $V_0 \simeq 0.6$ volts. Rectifiers made of silicon with the diffusion technique are able to pass hundreds of amperes per square centimeter continuously in the forward direction in areas up to 0.[illegible] square centimeter. One type of device whose area is 0.06 cm² readily conducts ten amperes with less than one volt forward drop. The forward current voltage characteristic of this family of rectifiers follows an almost exponential characteristic indicating that

R_s is extremely small (<0.05 ohms). Although the measured reverse currents are greater than those predicted by theory for temperatures up to 100°C, the reverse losses are low and do not affect the efficiency appreciably.

1.4 The diodes made by the diffusion of silicon are very attractive from an engineering standpoint for several reasons. First of all, their behavior is predictable from the theory of semiconductor devices, as are junction transistors. This makes it possible to design rectifiers of given electrical, thermal, and mechanical characteristics. Secondly, rectifier elements of many sizes are availahle from the same diffused wafers making it possible to use the same diffusion process, material, and equipment for a range of devices. Thirdly, large enough elements can be processed so that the power dissipation in the unit is limited only by the thermal impedance of mount and package.

2.0 DIFFUSION PROCESS

2.1 It will be shown in 3.2 that the forward characteristic of these devices is practically independent of the type (n or p) and resistivity of the starting material. The reverse breakdown voltage of a silicon p-n junction depends primarily on the resistivity of the lightly doped region. With these two considerations in mind; that is, to fabricate rectifiers having the desirable excellent forward characteristic and at the same time high reverse hreakdown voltage, high resistivity silicon is used as the starting material for the diffused barrier silicon rectifiers. Single crystal material has been found to give a better reverse characteristic than multicrystalline material. Also, it has been found that p-type material has yielded units with a better reverse characteristic than n-type material. Therefore, in the remainder of this paper, we will limit discussion to rectifiers made from high resistivity, single crystalline, p-type silicon. We will designate this material as π type silicon.

2.2 In addition to the fine control one has in the diffusion process (see 2.4), the process lends itself admirably to the semiconductor rectifier field in as much as the distribution of impurities in this process results in a gradual transition from a degenerate semiconductor at the surface of the material to a non-degenerate semiconductor a short distance below the surface. This condition permits low resistance ohmic metallic contacts to be made to the surfaces of the diffused silicon.

In order to create a p-n junction in the π silicon, it is necessary to diffuse donor impurities into one side of the slice. Although several donor type impurities have been diffused into silicon, all the devices discussed

in this paper were fabricated by using phosphorus as the donor impurity. In order to make the extremely low resistance contact to the π side of the junction that is desirable in rectifiers, acceptor impurities are diffused into the opposite side of the π silicon slice. Boron was selected from the several possible acceptor type impurities to use for the fabrication of these devices. A configuration of the diffused slice is shown in Figure 2.

2.3 It will be shown in Section 3 that there are limits to the thicknesses of the three regions, $N+$, π, $P+$, due to the nature of the operation of these rectifiers. With present techniques, it is necessary to keep

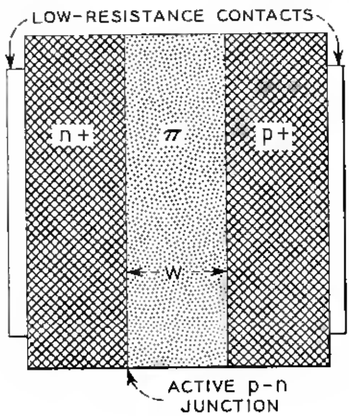

Fig. 2 — Diffused silicon rectifier configuration.

the thickness of the π region to the order of two or three mils (thousandths of an inch).

2.4 In the diffusion process of introducing impurities in silicon for the purpose of creating junctions or ohmic contacts, the diffusant is deposited on the silicon and serves as an infinite source. The resulting concentration of the diffusant is given by

$$C = C_0 \left[1 - \frac{2}{\sqrt{\pi}} \int_0^{x/\sqrt{4Dt}} e^{-y^2}\, dy \right] \tag{1}$$

$$= C_0 \operatorname{erfc} y$$

where C = concentration at distance x below surface
C_0 = concentration at surface
D = diffusion constant for impurity at temperature of diffusion

t = total time of diffusion

$y = \dfrac{x}{\sqrt{4Dt}}$ = variable of integration

A plot of $C/C_0 = \operatorname{erfc} y$ versus y is given in Fig. 3. C_0 is the surface solubility density and depends upon the temperature of the diffusion process.[4] At some depth, x_j, the concentration C equals the original impurity concentration where the silicon will change conductivity type resulting in a junction. In order to obtain desirable depths of the diffused layers, $N+$ and $P+$, it is necessary to diffuse at temperatures in the range of 1000°C to 1300°C for periods of hours. With such periods it is obvious that the diffusion process lends itself to easy control and reproducibility.

3.0 CONDUCTIVITY MODULATION

3.1 It is well known that the series resistance of a power rectifier is the most important electrical parameter to control and should be made as small as possible for several reasons. The series resistance consists essentially of two parts; the body resistance of the semiconductor and the contact resistance to the semiconductor. In the early stages of rectifier development both parts of the series resistance contributed about equally to the total series resistance. However, methods were soon found to reduce the contact resistance. It then became apparent that in order to reduce the body resistance, the geometry would have to be changed and the resistivity chosen carefully. By going to larger, thinner wafers it was possible to reduce this body resistance. However, the cost of pure silicon made it important that conductivity modulation (described below) be incorporated in these devices as a method for reducing the body resistance. Our initial attempts were successful due to the fact that higher lifetime of minority carriers could be maintained in the extremely thin wafers that were used as compared to the lifetime remaining after the diffusion process in thicker wafers.

3.2 A complete mathematical description of the I–V characteristic for the conductivity modulated rectifier is practically impossible due to the fact that the equations are transcendental. However, it is easy to understand the operation of the device physically.

When the device is biased in the forward direction, electrons from the heavily doped $N+$ region are injected into the high resistivity π region. If the lifetime for these electrons in the π region is long enough, the electrons will diffuse across the π region and reach the $P+$ region

[4] Fuller, C. S., and Ditzenberger, J. A., J. Appl. Phys., **25**, p. 1439, 1954.

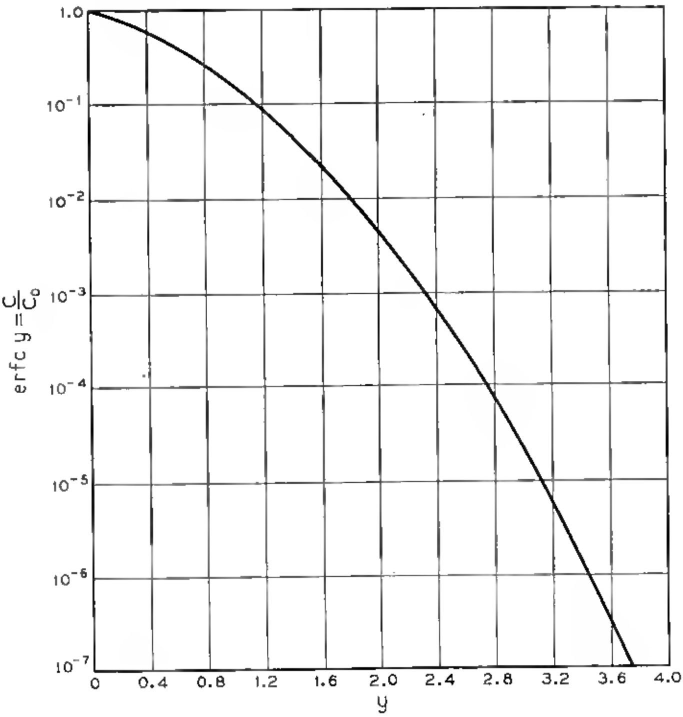

Fig. 3. — Error function complement.

with little recombination. To maintain electrical neutrality, holes are injected into the π region from the $P+$ region. These extra mobile carriers (both electrons and holes) reduce the effective resistance of the π layer and thus decrease the voltage drop across this layer. The higher the current density, the higher is the injected mobile carrier densities and therefore, the lower is the effective resistance. It is for this reason that the process is termed conductivity modulation. This effect tends to make the voltage drop across the π region almost independent of the current, resistivity, and semiconductor type.

When the junction is biased in the reverse direction, a normal reverse characteristic with an avalanche breakdown is expected and observed.

3.3 The forward characteristic of a typical unit is plotted semilogarithmically in Fig. 4. The best fit to the low current data can be

expressed as

$$I = I_0 e^{qV/NkT} \tag{2}$$

where I = current thru unit
I_0 = constant
q = charge of electron
V = voltage across unit
k = Boltzmann's constant
T = absolute temperature
and $1 < N < 2$.

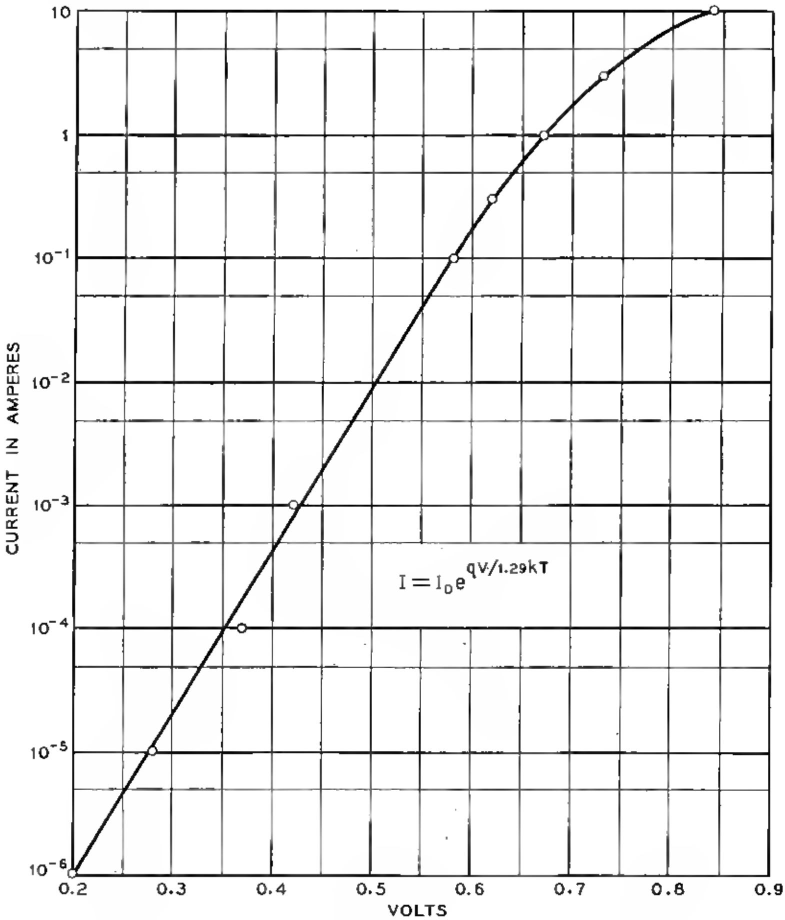

Fig. 4 — Forward characteristic of silicon power rectifier.

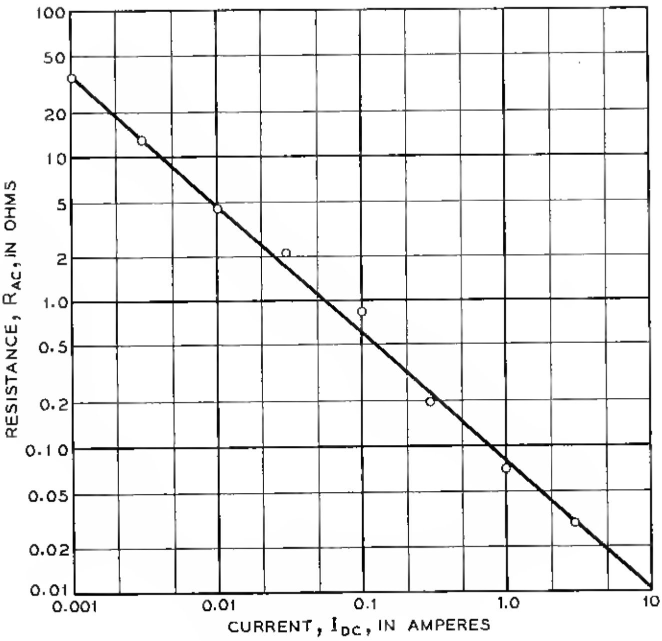

Fig. 5 — Small signal resistance versus dc forward current.

The departure of the high current data from the exponential characteristic is due to the contact resistance. Another interesting measurement of the forward characteristic is given in Fig. 5 where the small signal ac resistance is plotted as a function of the forward dc current for a typical rectifier element. The departure from the simple rectifier theory[5] where $N = 1$ is not surprising inasmuch as p-n junctions made by various methods and of different materials almost always have $N > 1$. Several calculations have been carried out using different assumptions and all indicate that the forward characteristic is independent of the type and resistivity of the middle region as long as the diffusion length for minority carriers is the order of or larger than the thickness of the region.

3.4 In order to go to higher reverse breakdown voltages (>500 volts) it is necessary to use still higher resistivity starting material. It might be expected that intrinsic silicon will be used for the highest reverse breakdown voltages when it becomes available. However, in this case

[5] Shockley, W., B.S.T.J., **28**, p. 435, 1949.

thick wafers are necessary since the reverse biased junction space charge region extends rapidly witb voltage for almost intrinsic material, and high lifetime is necessary in order to get the conductivity modulation effect in these thick wafers. Therefore at present it is necessary to compromise the highest reverse breakdown voltages with the lowest forward voltage drops, in a similar manner to that discussed in Section 1. However this is now done at a different order of magnitude of voltage and current density.

4.0 FABRICATION OF MODELS

4.1 It has been pointed out in Section 1.2 that a low series resistance, R_s, is desirable and that it is composed of two parts; the body resistance and the contact resistance. In Section 3 a method for reducing the body resistance was described. The contact resistance can also be made very low. It has been found to be very difficult to solder low temperature solders (M.P. up to 325°C) to silicon with any of the standard commercial fluxes. However, it is quite easy to plate various metals to a surface of silicon from an electroplating bath or by an electro-less process[6] to which leads can readily be soldered. Some metals used for plating contacts are rhodium, gold, copper, and niekel. This type of contact yields a low contact resistance. Another technique that has shown some promise for making the necessary extremely low resistance contact is the hydride fluxing method.[7]

4.2 A wafer which may be about one inch in diameter is ready to be diced after it is prepared for a soldering operation. Up to this point all the material may undergo the same processing. Now it is necessary to decide how the prepared material is to be used; whether low current ($\sim$1 amp) devices or medium or high current ($\sim$10–50 amps) devices are desired. The common treatment of all material for the entire class of rectifiers is one reason these devices are highly attractive from a manufacturing point of view.

The dicing process may be one of several techniques; mechanical cutting with a saw, breaking along preferred directions, etching along given paths with chemical or electrical means after suitable masking methods, etc. In the case of mechanical damage to the exposed junctions, the dice should be etched to remove the damaged material. The dice are cleaned by rinses in suitable solvents and are then ready for

[6] Brenner, A., and Riddell, Grace E. J., Proc. American Electroplaters' Society, **33**, p. 16, 1946, **34**, p. 156, 1947.

[7] Sullivan, M. V., Hydrides as Alloying Agents on Silicon, Semiconductor Symposium of the Electrochemical Society, May 2–5, 1955.

assembly into the mechanical package designed for a given current rating.

4.3 The dice may be tested electrically before assembly by using pressure contacts to either side. Pressure contacts have been considered for packaging the units; however, this type of contact was dropped from development due to mechanical chemical, and electrical instabilities.

4.4 The drawbacks of the pressure contact make it important to find a solder contact that does not have the same objections. The solder used should have a melting point above 300°C, be soft to allow for different coefficients of expansion of the silicon and the copper connections, wet the plated metal, and finally, be chemically inactive even at the high temperature operation of the device. These requirements are met with many solders in a package that is hermetically sealed. This combination of a solder and a hermetically sealed package has been adopted for the intermediate development of the diffused silicon power rectifiers.

5.0 ELECTRICAL PERFORMANCE CHARACTERISTICS

5.1 Before describing the electrical properties of these diodes, let us consider some of the physical properties of a few members of the class.

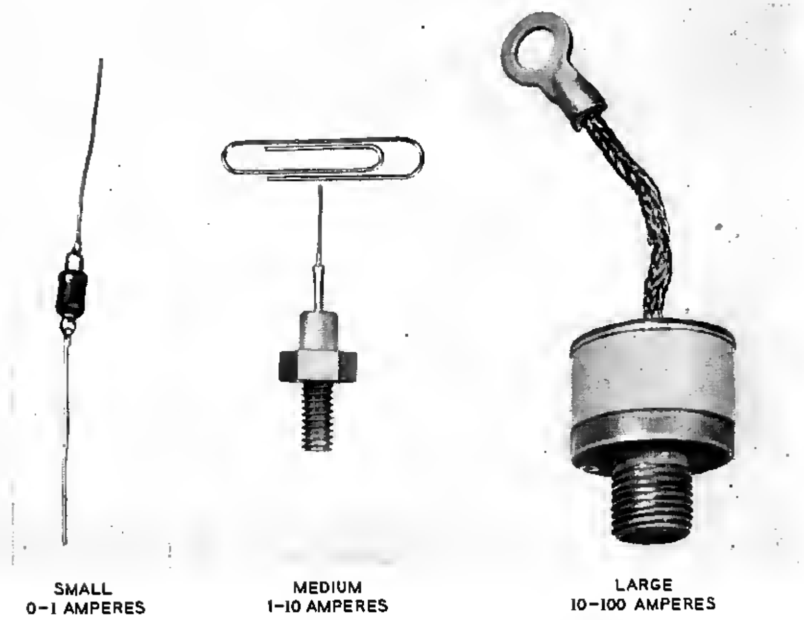

Fig. 6 — Development silicon rectifiers.

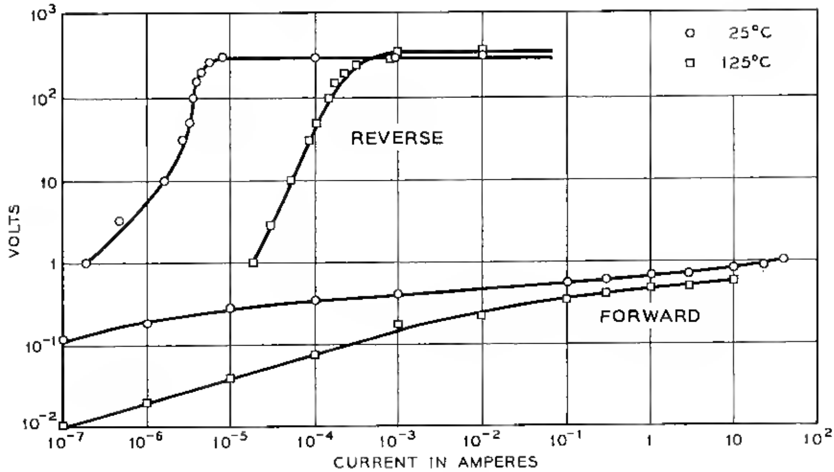

Fig. 7 — I-V characteristic of medium size rectifier.

Fig. 6 shows a picture of three sizes of units that will be discussed in this section together with the range of currents that these units can conduct. The actual current rating will depend upon the ability of the device to dispose of the heat dissipated in the unit. A description of how the rating is reached is given in Section 6.

The smallest device has a silicon die that is 0.030″ by 0.030″ in area

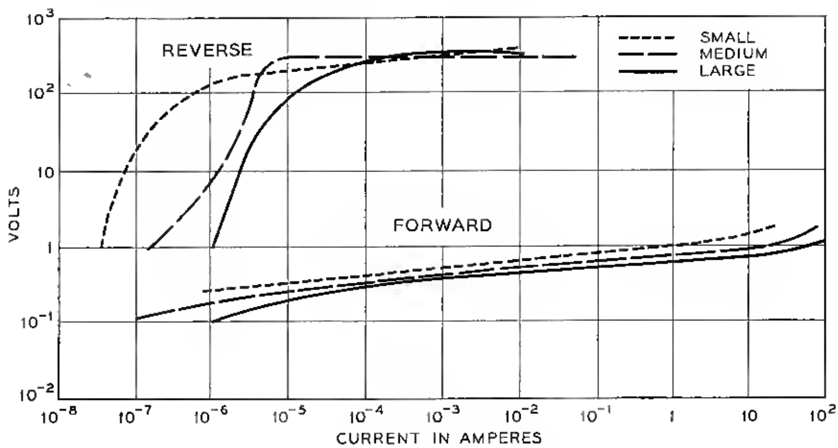

Fig. 8 — I-V characteristics of development rectifiers.

and all the units have dice about 0.005″ thick. The medium size device has a wafer 0.100″ by 0.100″ in area. The largest device has a element 0.250″ by 0.250″ in area. It is obvious that a range of die size could have been chosen for any of these rectifiers. However, electrical and thermal considerations have dictated minimum sizes and economic considerations have suggested maximum sizes. The actual sizes are intermediate in value and appear to be satisfactory for the given ratings.

5.2 Of fundamental importance to users of these rectifiers are the forward and reverse current — voltage characteristics. These characteristics of the medium size unit are shown in Fig. 7 for two temperatures, 25°C and 125°C, using logarithmic scales. It can be seen that in the forward direction at room temperature, 25°C, more than 20 amperes are conducted with a one volt drop in the rectifier. At the higher temperature more current will be conducted for a given voltage drop. In the reverse direction, this particular unit can withstand inverse voltages as high as 300 volts before conducting appreciable currents (>1 ma) even at 125°C. A comparison of the current-voltage characteristics for the three different size units is shown in Fig. 8 where again the information is plotted on logarithmic scales. This information was obtained at 25°C. One can observe that the reverse leakage current varies directly as the area of the device and the forward voltage drop varies inversely as the area. These relations are to be expected; however, the reverse characteristics indicate that surface effects are probably effecting the exact shape of the curves. The changes in the forward characteristics can be attributed to the contacts and the internal leads of the packages. The breakdown voltage can be adjusted in any size device by the proper choice of starting material and therefore no significance should be placed on the different breakdown voltages in Fig. 8.

Fig. 9 — Semiconductor rectifiers of different materials.

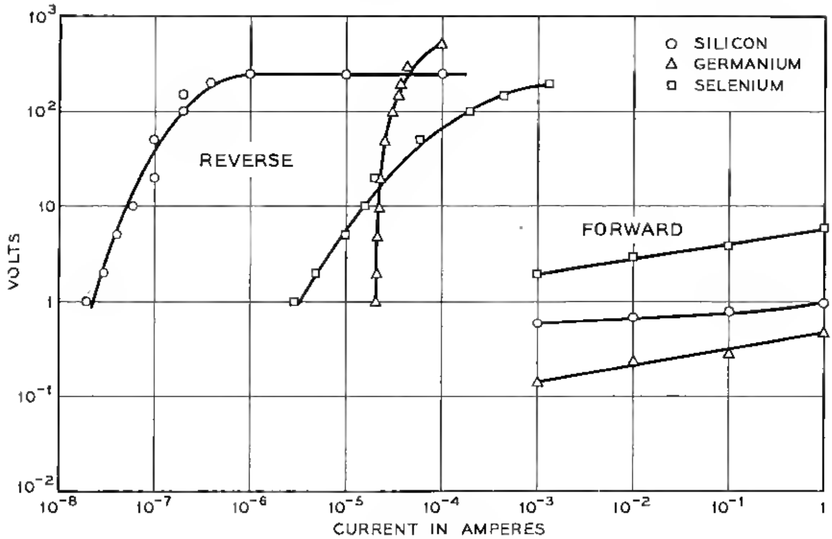

Fig. 10 — Rectifier characteristics at 25°C.

It is quite interesting to compare these units with germanium and selenium rectifiers that are commercially available. To make the comparison as realistic as one can, we have chosen to compare the smallest silicon unit with a commercially available germanium unit and a six element selenium rectifier stack rated at 100 milliamperes. The comparative size of these units can be seen in Fig. 9. Curves of the forward and reverse characteristics at 25°C are given in Fig. 10. Similar curves taken at 80°C are given in Fig. 11 and at 125°C in Fig. 12. It can be seen that the forward characteristic is best for the germanium device at all temperatures and that the reverse currents are least for the silicon rectifier. The selenium rectifier is a poor third in the forward direction. However, if one has to operate the device at 125°C, only the silicon device will be satisfactory in both the forward and reverse directions.

5.3 Capacitance measurements of all the silicon units have been made at different reverse voltages and temperatures. The temperature dependence is negligible. However, as expected in semiconductor rectifiers, the capacitance varies inversely with the voltage according to the relation VC^N = constant where $2 < N < 3$. Measurements are given in Fig. 13 for a group of medium size units. The other units made from the same resistivity material have capacitances that vary directly as their areas.

5.4 The reverse breakdown voltage, V_B, of these devices is controlled by the choice of resistivity of the starting material and the depth of diffusion of the junction. By keeping the resistivity of the initial p-type silicon above 20 ohm-cm., it is possible to keep V_B above 200 volts. Units have been made with V_B greater than 1,000 volts. The deeper diffusion causes the junction to be more "graded"[5] and therefore require a greater voltage for the breakdown characteristic. This is in line with the capacitance measurements where the exponent indicates that the junction is neither a purely abrupt junction which would result in an exponent of two nor a constant gradient junction which would result in an exponent of three.

5.5 Another interesting measurement, which is related to the lifetime of minority carriers in the high-resistivity region and the frequency response, is the recovery time of these devices. During a forward bias on a p-n junction, excess minority carriers are injected into either region. When the applied voltage polarity is reversed, these excess minority carriers flow out of these regions, giving rise initially to a large reverse current until the excess carriers are removed. The magnitude and time variation of this current will depend to some extent upon the level of the forward current but mostly upon the circuit resistance. If one adjusts the circuit resistance such that the maximum initial current in

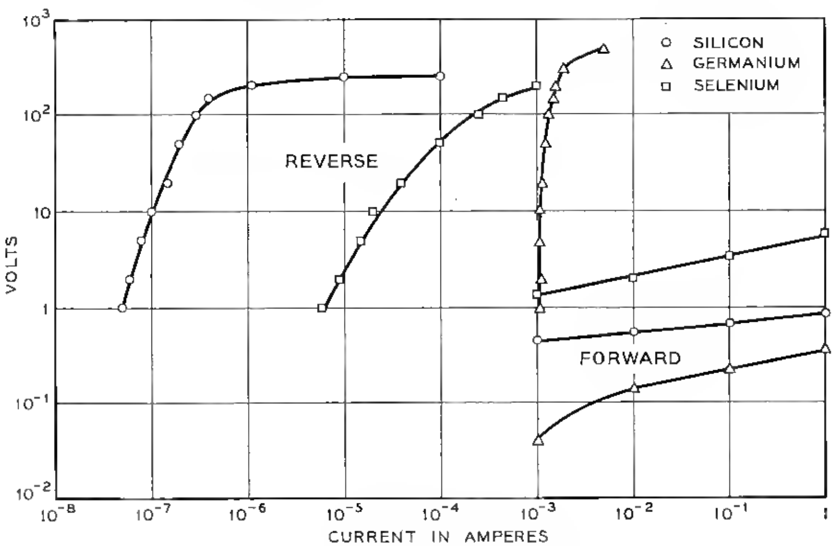

Fig. 11 — Rectifier characteristics at 80°C.

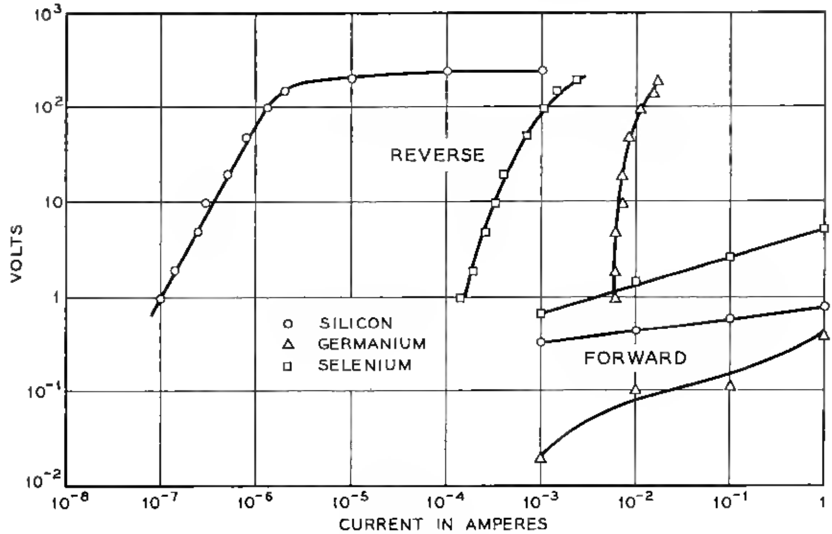

Fig. 12 — Rectifier characteristics at 125°C.

the reverse direction is equal to the forward current before reversing the polarity of the junction, then the reverse current will have a constant magnitude, limited by the circuit resistance, for a time known as the recovery time before it decays to a small steady-state value. Fig. 14 shows graphically this effect. The recovery time in diffused junctions is found to be in the range of less than 0.1 microsecond to more than 4

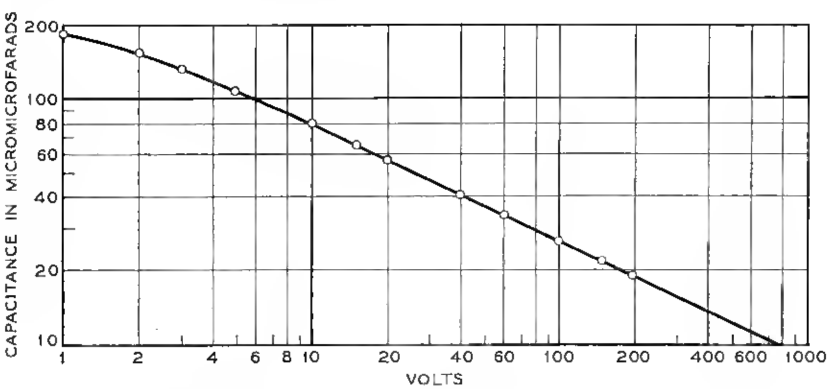

Fig. 13 — Capacitance versus reverse voltage in medium size rectifer.

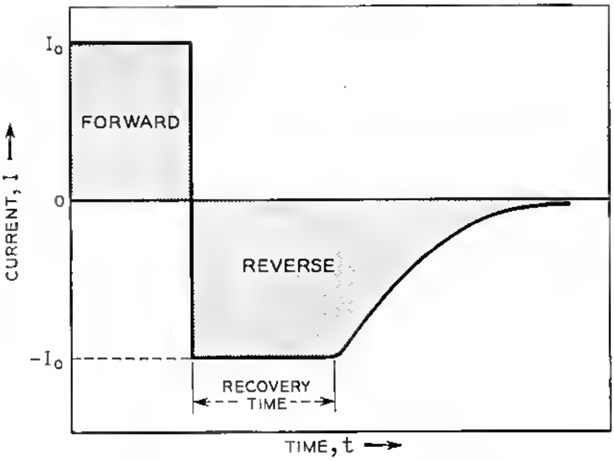

Fig. 14 — Recovery effect in silicon rectifiers.

microseconds. It can be shown that the longer recovery times are associated with higher lifetimes of minority carriers. More interesting, however, is the fact that these devices will have their excellent rectification characteristics to frequencies near the reciprocal of the recovery time. Measurements have been made of the rectification ability of typical small and medium size units by using the circuit shown in Fig. 15. The results of normalized rectified current versus frequency are given in Fig. 16 and it is seen that these units could be used to rectify power up to 1 kc/sec without any appreciable loss of efficiency.

5.6 It is interesting to note that many of the electrical measurements made with the diffused barrier silicon rectifiers are self-consistent and can be related to simple concepts of semiconductor theory. As an example, experimental measurements indicating variations of recovery time of units are related to variations in minority carrier lifetime which in turn are related to experimental variations in the forward characteristic

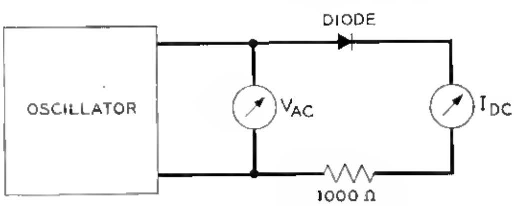

Fig. 15 — Rectification measuring circuit.

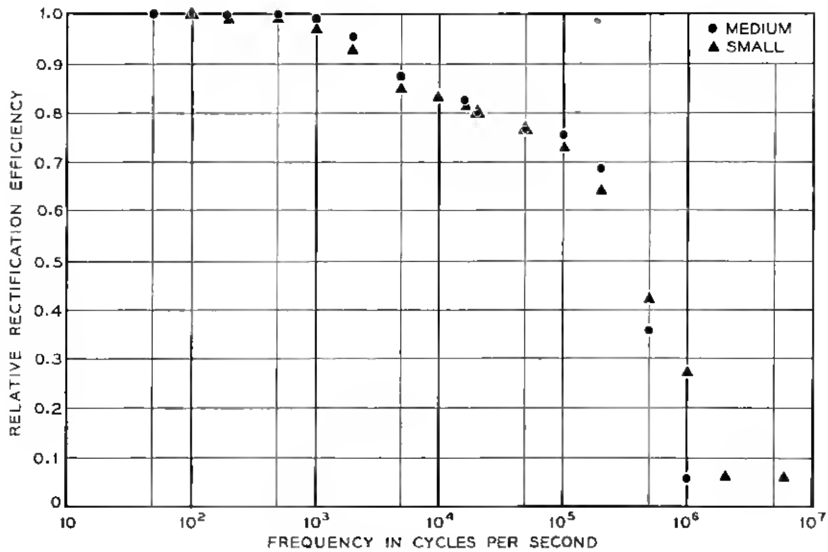

Fig. 16 — Relative rectification efficiency versus frequency.

of these same devices. Such relationships among the measurable parameters of these devices make it possible to design and control the electrical characteristics of the units and therefore make them extremely attractive from an engineering point of view.

6.0 MECHANICAL AND THERMAL DESIGN

6.1 In order to have a device that is usable for more than experimental purposes, it is necessary that it be packaged in a mechanically stable structure and that the heat generated in the combined unit should not lead to a condition where the device no longer has its desirable characteristics. In earlier sections of this paper several mechanical requirements of a satisfactory package have been suggested. These may be repeated at this point. First, pressure contacts are not satisfactory; second, oxidizing ambients are to be avoided; third, approximately one watt per ampere of forward current is generated and must be disposed; and fourth, the package must be electrically satisfactory. The first requirement is met by using soldered contacts. Since these rectifiers are usable at temperatures over 200°C, a solder was chosen that has a melting point over 300°C. The second requirement necessitated the use of a hermetic seal structure. If the seal is truly hermetic, no gases can

enter or leave the package and thus no changes of the device due to the enclosed gas should occur as long as the gas does not react with the silicon, solder or package. However, no seal is absolutely vacuum tight and thus care should be used in choosing a package design so that minimum effects should occur to the electrical properties during the use of the device. The third requirement of the disposal of the internally developed heat suggested the use of copper due to its high thermal conductivity. However, a small package alone is capable of dissipating only a small amount of heat without reaching a temperature that is too high for the device. This necessitates the use of cooling fins in conjunction with the device to make use of its electrical properties. This thermal requirement demands a package to which thermal fins can be attached. This is met by having the package contain a bolt terminal to which thermal fins can be attached or by which the unit can be mounted to a chassis for cooling. The fourth requirement consists of two parts; the package must have two leads tbat are electrically separated from one another and the leads must be sufficiently heavy to conduct the maximum currents. The first of these requirements is met by using glass-to-metal seals in the package and the second is met by using copper leads of sufficiently heavy cross-section. The resulting packages for the units discussed in this paper are shown in Fig. 6. It should be remembered that the packages are only intermediate development packages and that further work will probably alter these both in size and in shape. However, all the requirements mentioned will be applicable to any package.

6.2 The units pictured in Fig. 6 have a range of dc current ratings associated with them. The lower rating of each device corresponds to the maximum rating of the next smaller device. Of course, the larger units could be used for smaller current applications; however, such use would be like using a freight car to haul a pound of coal. The maximum rating of each device has been arbitrarily chosen for it to operate with a reasonable sized cooling fin at an ambient of 125°C and no forced air or water cooling. It is known that the ratings could be increased by either method of forced cooling. It has been found that a copper convection cooling fin is able to dissipate 8 milliwatts per square inch per degree centigrade. This cooliug rate is obtained from the difference between the average temperature of the fin and the ambient temperature over the effective exposed area of the fin. For example, a copper fin 3½ inches square when mounted so that both surfaces are effective for cooling will be able to dissipate ten watts and at the same time prevent the temperature of the fin from exceeding 50°C above the ambient temperature. Another thermal drop is found between the junction and the

base of the package. This temperature difference depends mostly on the material of the base and its geometry. In the devices presented this drop is not more than 15°C at the maximum rated current. Thus the largest drop in temperature occurs between the cooling fin and the ambient which means that the design of the cooling fin is the controlling factor in the operating junction temperature of the rectifier.

6.3 It is possible to use the devices without an attached cooling fin. In this case, the maximum current is limited essentially by the size of the package. The small rectifier package is designed for ½ watt dissipation and therefore the maximum current that should be rectified is about 500 milliamperes. The medium size unit will comfortably rectify 1 ampere without any additional cooling and the large rectifier unit will conduct 3 amperes under the same conditions.

7.0 RELIABILITY AND LIFE MEASUREMENTS

7.1 One of the desired properties of any device is that it should operate satisfactorily at its rating for a long period of time. The above general statement contains many implications which should be made specific for the devices under consideration in this paper. By stating that these devices should operate satisfactorily we mean that they should not age during operation; that is, the forward and reverse characteristics at any temperature should not change with time. The statement implies that a rating has been established for the units. Furthermore, a "long period of time" has to be defined. There are applications where a few hours is considered a long time as in some military applications. However, in most Bell System applications, a long period of time may be 20 years or approximately 200,000 hours. Clearly, in the short time since these rectifiers have been developed, it is impossible to make a fair statement as to their reliability and their life expectancy. However, it is possible to present some results of some early experiments and describe where and how the units have lived and died. It is this information that we will present in this section. It is a common experience that during the early development of any new component, there are many units that do not satisfy all the requirements of the desired end product. These units will generally deteriorate very rapidly on life testing due to some electrical or mechanical instability. The units used for life testing have been screened to remove the above mentioned unstable devices.

7.2 The life tests consist of four types; shelf tests at room temperature and at 150°C, forward characteristic tests, reverse characteristic

tests, and load tests. The last tests are really the important tests; however, these require the dissipation of large quantities of power in the load to test only a few devices. Therefore only a few units were tested in this condition and the majority tested under other conditions. The several units under load test have been operating for six months with no noticeable change in their characteristics. These devices are the small and medium size development units. The large rectifiers would require about 10 kilowatts of dissipation each in a load to give them a fair load test.

The shelf tests at room temperature and at a temperature of 150°C have been running for six months and have indicated that most of the units remain practically constant. There have been some units that improve on standing but there is no method of predicting which ones will improve. Some units get worse on standing; however, most of these can be predicted from the initial tests since these units usually have a noisy reverse characteristic near the reverse breakdown voltage. The units that change differ only in their reverse characteristic; the forward characteristic changes are not detectable indicating that the contacts are stable. The changes in the reverse characteristic are probably due to the trapping of ions and vapors on the surface of the devices during the packaging operation. Another source of these variations is due to the non-hermeticity of the glass-to-metal seals allowing gases to diffuse into the package where they may cause changes in the reverse characteristic. These leaks have been found in many early units and new assemblies are being tried at present.

The forward characteristic life test was considered a good test since the device is subject to practically all the internal power dissipation without requiring the relatively high load dissipation. It is tests of this nature that allow one to rate the various size devices. The medium size rectifiers that ran at 15 amperes in this test failed after three months of testing; whereas no units running at 5 and 10 amperes have failed during the six months since the tests have started although their reverse characteristics have changed slightly. It should be noted that most of the change of reverse characteristic occurred during the first test period of two weeks. These changes are probably due to the causes mentioned in the above paragraph.

Reverse characteristic tests have been running for several months on a group of 10 small rectifiers which we feel have a better gas tight seal than the other development units. The voltage has been adjusted on these units such that they are pulsed into the breakdown region with a

maximum current of one milliampere. None of these units show any appreciable change.

7.3 All of those tests in the past sub-section had to do with continuous dc or ac power being supplied to the units under test. However, in actual operation the units may be subject to voltage pulses due to power line pulses, accidental shorts, etc. In order for the rectifier to be useful, it should be able to take an overload for a period of time sufficiently long to allow a protective device to operate. Pulse tests have been performed on the medium size rectifier. These devices are able to withstand over 300 amperes for times of the order of 50 microseconds. However, the fastest circuit breakers operate in about 20 milliseconds and for this period, these units can stand only approximately 50 amperes before failing. Since these units have such a low forward resistance at the operating currents (Fig. 7), any small increase in voltage across the diode will change the current through the device to a very large quantity. Therefore series protective resistances may be necessary where the possibility of short-circuiting the device is high. Such operation would reduce the efficiency of the unit and is to be avoided if possible. Another type of protection may be afforded through the use of a high impedance, high current inductor. This type of protection is quite bulky and heavy and suitable only for stationary apparatus. Another common possibility of burnout of the devices occurs when using a capacitance input in conjunction with the rectifier. When the circuit is turned on, large currents will flow to charge up the capacitors and consequently burn out the rectifiers. One possible protection from such operation is the use of a series resistance in conjunction with a time delay relay. The series resistance will limit the initial capacitor charging current and the time delay relay will short out the resistance after the capacitors have reached near their maximum charge.

7.4 Dissection of burned out units have indicated that the failure takes place through small spots on the device. This can be explained by the fact that some small areas of the device have slightly better forward characteristics. These areas will tend to conduct most of the forward current. Therefore most of the power will be dissipated there and these areas will become even more conducting leading to a channeling of the forward current through these spots with the consequent burnout. The best way to avoid such mishaps would be to make a more uniform device. Experiments are in process along this line. Another less satisfactory method would be the control of contact resistance such that the current would be limited in any particular area by the contact resistance. Similar ideas must be considered when paralleling these diffused junction

silicon rectifiers. It is possible to use these devices in parallel if one adjusts the lead resistances such that no one unit will be allowed to conduct much more than its share of the current.

7.5 As a conclusion to this section, it should be noted that these rectifiers are expected to have a long life when operated within their ratings. They are able to operate for short periods of time (seconds) at five times their rated currents. Since the rectifiers have an extremely small series resistance, they should be protected against accidental surges and turning on to a capacitance input filter.

8.0 SUMMARY

8.1 The development rectifiers described in the article are silicon diffused p-n junction rectifiers. These devices together with associated cooling fins can be used to rectify a complete range of currents from 0 to 50 amperes in a single phase, half wave rectifier circuit. They can be used in more complex rectification circuits to yield even more dc current. Also, they are able to withstand at least 200 volts peak in the inverse direction and operate satisfactorily at temperatures as high as 200°C. Furthermore, one process of diffusion and plating is sufficient for all the devices of the class. This makes it possihle for one diffusion and plating line to feed material for all the rectifiers in a manufacturing operation.

8.2 The rectifiers discussed behave according to the theory of semiconductor devices which makes it possible to design them for given electrical, thermal, and mechanical characteristics. One failure to meet ideal theory of a p-n junction is with the forward characteristic.

8.3 The diffused silicon type of rectifier has been compared with germanium and selenium units and has better reverse characteristics at all temperatures. In the forward direction, the germanium units have a smaller voltage drop for any given current than the silicon rectifiers but the silicon devices are capable of operating at much higher temperatures, thereby permitting higher overall current densities than the germanium devices.

8.4 The diffused silicon rectifiers are capable of use in any rectifier application where dc currents up to the order of 100 amperes are required and where inverse peak voltages up to 200 volts are encountered. Another important use for these devices will be in the magnetic amplifier application where the low reverse currents of silicon will enable large amplification factors to be realized. Since the forward characteristics of these devices are so uniform, they can be used in voltage reference circuits that require voltages near 0.6 volts and in circuits uti-

lizing the exponential character of the forward characteristic. However, as is to be expected from devices with the characteristics described in this paper, the most immediate application will be found in power supplies.

ACKNOWLEDGMENTS

It is obvious that the work reported in this paper is not the result of one man's labor. Much of the stimulus and many of the ideas are those of K. D. Smith. Other members of the Semiconductor Device Department who have contributed considerably to the development of these devices are R. L. Johnston, R. Rulison, and R. C. Swenson. D. A. Kleinman, J. L. Moll and I. M. Ross have been most helpful in discussing the theoretical aspects of these devices. The author wishes to thank H. R. Moore for his suggestions on protecting the silicon rectifiers against large overloads.